Range-depths tracking of multiple sperm whales over large distances using a two-element vertical array and rhythmic properties of clicks-trains

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Abstract

Sperm whales (*Physeter macrocephalus*) have followed fishing vessels off the Alaskan coast for decades, in order to remove sablefish ("depredate") from longlines. The Southeast Alaska Sperm Whale Avoidance Project (SEASWAP) has found that whales respond to distinctive acoustic cues made by hauling fishing vessels, as well as to marker buoys on the surface. Between 15-17 August 2010 a simple two-element vertical array was deployed off the continental slope of Southeast Alaska in 1200 m water depth. The array was attached to a longline fishing buoyline at 300 m depth, close to the sound-speed minimum of the deep-water profile. The buoyline also served as a depredation decoy, attracting seven sperm whales to the area. One animal was tagged with both a LIMPET dive depth-transmitting satellite and bioacoustic B-probe tag. Both tag datasets were used as an independent check of a passive acoustic scheme for tracking the whale in depth and range, which exploited the elevation angles and relative arrival times of multiple ray paths recorded on the array. The localization approach doesnt require knowledge of the local bottom bathymetry. Numerical propagation models yielded accurate locations up to at least 35 km range at Beaufort sea state 3. Ongoing work includes combining the arrival angle information with an algorithm developed by Le Bot *et al.* [1] that uses the rhythmic properties of odontocete click trains to separate interleaved click trains. This approach will improve our localization capabilities in presence of multiple sperm whales. In order to achieve better separation of interleaved click trains it is possible to use machine learning based algorithms. This new concept is based on finding useful information hidden in a large database. This useful information can then be represented by a sparse subspace. The first step of the approach is to extract informative features with a

new detector proposed by Dadouchi *et al.* [2]. Once the dictionary of features is learned, any signal of this considered dataset can be approximated sparsely. By reducing the dimensional space, the sparse representation has the advantage to provide an optimally representation of the data. [Work supported by the North Pacific Research Board, the Alaska SeaLife Center, ONR, NOAA and ANR-12-ASTR-0021-03 "MER CALME"]

1 Introduction

In recent years, passive acoustic methods have become increasingly widespread for monitoring the general assessment of marine environments [2]-[4] and expanding knowledge about marine mammals vocalization repertoire, distribution and habitat characterization. In the past decade, considerable efforts have been made for this purpose using a combination of ocean science, signal processing, statistics and computational (algorithms) science [5].

This paper is concerned with the localization and tracking of sperm whales using a vertical array comprising only two hydrophones. Indeed, passive acoustic monitoring has become an important tool to study sperm whale behavior in the Gulf Of Alaska and their interaction with longlining fisheries [6]-[7]. Each click event generated by a sperm whale can arrive on a hydrophone via multiple ray paths. In this paper, the ray path that arrives first on a hydrophone will be called the primary path, and other ray path arrivals that arise from the same click event are called secondary paths, or multipath.

Most methods developed for localizing marine mammals use wide-baseline hydrophone arrays and the time-difference-of-arrival (TDOA) of a sound on pairs of hydrophones [8]-[10]. Methods are often based on ray-trace acoustic propagation modeling and exploit multipath arrival information from recorded sperm whale clicks. The algorithm compares the arrival pattern from a sperm whale click to range and depth dependent modeled arrival patterns in order to estimate whale location. The technique can account for waveguide propagation physics like interaction with range-dependent bathymetry and ray refraction. Tieman *et al.* [11] managed to track a sperm whale in three dimensions using only one acoustic sensor and a model of the azimuthally dependent bathymetry.

When multiple whales are simultaneously clicking, the biggest challenge is to arrange clicks into separate click-trains corresponding to individual whales, and then classify clicks as primary paths and multipaths. In the past decade several authors proposed algorithms for separating multipaths from the primary click-train, either on single hydrophones [11] two-hydrophone arrays [12] or wide-baseline acoustic arrays [13]. These algorithms exploit the slowly varying multipath structure of individual whales or the slowly varying features of clicks within a train (such as waveform, power). Recently, a few papers discussed how sparse coding can be an effective technique for solving the multiple-marine mammal tracking problem [14]-[17]. Sparse coding seems to be a promising alternative to usual time-frequency feature analysis.

To our knowledge the long-range tracking of multiple whales on a single deployment has not been performed yet. For many applications, the deployment of several hydrophones is impractical and too expensive. Here we discuss how a two-element vertical was used to track the range of multiple whales up to a 35 km range over a 3-day period and how the method could be automated using rhythmic properties of click-trains and sparse coding.

2 Semi-Automated tracking of multiple whales

A two-element vertical array deployed at the sound speed minimum was used to track sperm whales in the Gulf of Alaska between 15 and 17 August 2010. The vertical arrival angles and relative arrival times of multiple refracted and surface-reflected ray paths contain enough information for range-depth tracking without knowledge of the bottom bathymetry. A ray-tracing program was used to model the acoustic travel times from each candidate source location, using a measured sound speed profile. By comparing modeled and measured time lags and vertical angles, an ambiguity surface was created, displaying the best-fit whale position. A tagged sperm was tracked up to 35 km range under Beaufort 3 conditions, using satellite tag data to independently verify tracking estimates

(Mathias et al., 2013). The technique also permitted to measure the drift of multiple whales away from the vertical array. The method and results are described in detail in Mathias *et al.* [8].

However we were not able to automate the tracking process in the presence of as much as six whales simultaneously vocalizing. Techniques described above to separate click-trains such as the cross-correlation or a rhythmic analysis failed in our case, because of the high number of multipaths received at the hydrophones produced by whales at various ranges.

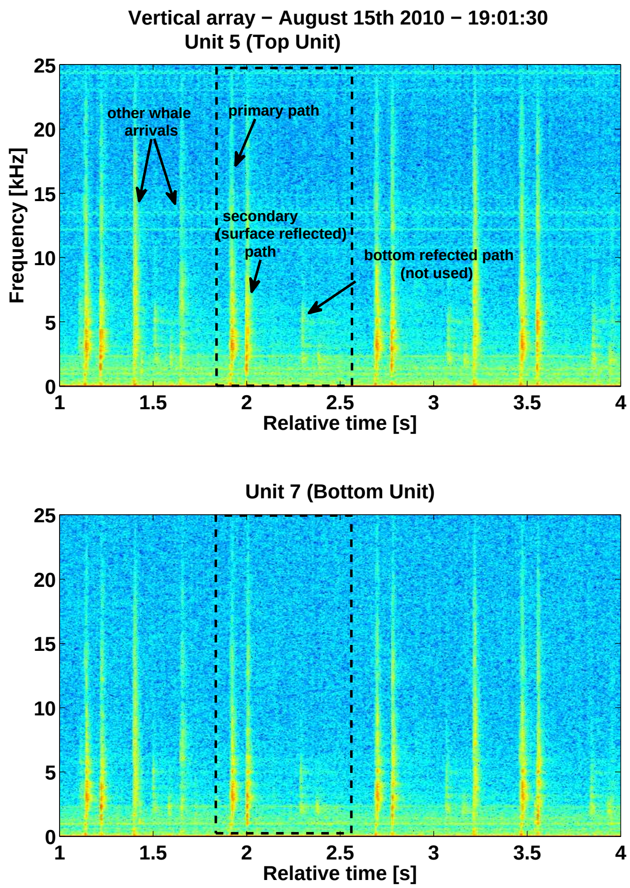

Figure 1: Spectrogram of multipaths produced by two sperm whales on 15 August 2010 at 19:01:30 and recorded on vertical array top and bottom hydrophones

3 Towards better localization of sperm whales using rhythmic properties of click-trains and sparse coding

Localizing a sperm whale using a two-element vertical array requires measuring the relative arrival times of at least two ray paths (the primary path and a multipath) on both hydrophones [8]. Therefore, we need to de-interleave click-trains and associate a primary path click-train with a multipath click-train. Two approaches seem promising for performing this task when three whales or more are vocalizing simultaneously. The first approach takes advantage of the two hydrophone array configuration and use the arrival angle information as an additional source of information for grouping sperm whale clicks into trains associated with a given whale and propagation path. Therefore on-going work includes combining the arrival angle information with an algorithm developed by Le Bot *et al.* [1] that uses the rhythmic properties of odontocete click-trains to separate interleaved click-trains. The algorithm only uses the time of arrival of each click and a complex- autocorrelation function to compute a histogram that exhibits peaks at inter-click intervals (ICI) corresponding to the interleaved click trains, while suppressing harmonics due to ICI multiples. This complex autocorrelation is calculated in a window sliding along the click train leading to a time-ICI representation, which is thresholded to detect the different interleaved click trains. This sequential search could use some complementary features such as the click arrival angle, level or its frequency content.

The second approach is based on sparse coding [18]-[19] and recent publications on the application of this technique on marine mammal sounds [14]-[17]. We propose that a sparse transform of the clicks in the time-frequency domain can help determine the stable components between multipaths belonging to an individual and a given propagation path. In order to reduce the signal dimension for more efficient computation, sets of Mel Frequency Cepstral Coefficients (MFCC) can be computed and a dictionary of features can be generated. Any click detected on the hydrophone can therefore be represented in this space of reduced dimension. The similary between each projected click can be computed using the cosine similarity measure for example. Glotin et al. 2013 showed that this technique worked for tracking the sounds produced by the same minke whale during 30 minutes. It is also possible to work directly on the spectrogram to select areas of interest. A specific algorithm by Dadouchi *et al.* [14]-[17] has been developed to detect click and whistles. Based on a two-stage methodology, this algorithm estimates the instantaneous frequency law of non-linear frequency modulations under several constraints (high resolution estimation, ability to cope with multiple overlapping and/or close signals in the time-frequency plane). The first step of the methodology is applied on the square modulus of any linear time-frequency representation, and aims at detecting the time-frequency support of the signals of interest under probabilistic models. A Chi-squared model is used to do the detection of time-frequency bins hosting signal, a Poisson model for the gathering of detected bins into regions of interest (RoIs). Once the RoIs are detected, a high resolution estimator using local polynomial frequency law estimation and phase continuity criteria is used to link local approximation to get a whole estimate of the instantaneous frequency law.

Acknowledgments

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